

**Close out and Final report for
NASA Glenn Cooperative Agreement NCC3-821**

Deformation and Damage Studies for Advanced Structural Materials

Introduction

Advancements made in understanding deformation and damage of advanced structural materials have enabled the development of new technologies including the attainment of a nationally significant NASA Level 1 Milestone and the provision of expertise to the Shuttle Return to Flight effort. During this collaborative agreement multiple theoretical and experimental research programs, facilitating safe durable high temperature structures using advanced materials, have been conceived, planned, executed. Over 26 publications, independent assessments of structures and materials in hostile environments, were published within this agreement. This attainment has been recognized by 2002 Space Flight Awareness Team Award, 2004 NASA Group Achievement Award and 2003 and 2004 OAI Service Awards. Accomplishments in the individual research efforts are described as follows.

HOTPC Rocketdyne—GRC Collaboration: Combustion Chamber Support Structure

Final contributions in structural design, analysis and mechanical testing were made within a Boeing Rocketdyne NASA-GRC collaboration addressing the development of lightweight combustion chamber support structure. Proposed novel designs and verification test methods to overcome difficult problem of thermal mismatch for dissimilar materials. Critical analyses of structural design options were made enroute to final prototype configuration for hotfire testing. Biaxial structural element tests were made to verify concept and calibrate analytical methods prior to hotfire testing. Publications report creative use of light weight design theory, upper bound analyses and novel concepts result in significant weight saving, outstanding safety margin for the prototype support structure. Developed rig fixtures for a unique series of planned biaxial structural element tests that will be used to verify concept and calibrate analytical methods. Also completed an independent assessment of possible structural performance anomalies due to thermomechanical fatigue of the support. Programmed complex MTS closed loop test control using TESTExpress software. A difficult program of thermomechanical fatigue testing to verify long-term durability of the composite was completed. Published theoretical assessment of unique design data notes sufficient safety margin to support manufacturing and hot fire testing to meet a nationally significant **NASA Level 1 milestone**. [2–4, 7–10, 12, 13, 17–19] This work was also coordinated with the Syracuse/Cornell NASA URETI providing an opportunity to disseminate NASA expertise in high temperature polyimide composites to graduate students. At the request of Prof. Barry Davidson of Syracuse University, acted as the GRC site technical mentor so that Ms. Christine Ganger could participate in additional durability studies associated with this HOTPC Program. This effort remains in progress but preliminary results are documented in internal presentations and a **Draft Report “Preliminary Assessment of Damage and Viscoelastic Effects in Stitched and Unstitched Cross-ply Graphite/Polyimide Laminates,” 2005.**

High Temperature Polyimide Composites for Reusable Launch Vehicles

Durability investigations of polyimide composites were also conducted in synergy with fundamental research with in the NASA Next Generation of Launch Vehicle program. Here the benefits of stitching to reduce steam induced delamination have been unequivocally demonstrated. Unique studies of residual compression test results show that wet conditioned materials have compressive strengths significantly greater than wet unstitched materials. This effort will be culminating with an **invited JANNAF paper** and a **2004 NASA Group Achievement Award** for determining the benefits and trade-offs for out of plane stitched polymer. [6, 12, 17, 22, 23, 25]

NASA Engineering and Safety Center (NESC) Composite Overwrap Pressure Vessel (COPV) Independent Technical Assessment (ITA)

Expertise was also provided to the NESC COPV ITA to investigate the stress rupture lifing and flight certification issues for Shuttle Return to Flight (RTF). This included participation in three Technical Interchange Meetings (TIM) held at JSC, LaRC and GRC. Filament wound Kevlar/Epoxy COPVs are an integral part of the space shuttle/orbiter system. Current ship sets have been in service since the first shuttle flights but since Kevlar fiber exhibits stress rupture due to sustained load the investigation was authorized by the NESC. The problem bears some similarity to issues with filament wound flywheel rotors and previous advancements [1] provided useful insight. Contributions were made in the areas of fundamental strength of materials, composite mechanics, damage tolerance and issues concerning experimental test methods. Fundamental analytical relations were derived and programmed to describe overwrap and liner interference fits, stresses and deformations including the effects of composite degradation and elastic-plastic liner response due to autofrettage. Corresponding Graphical methods were also developed to describe the non-linear relationship of applied pressure to Kevlar fiber stress/strain during manufacturing, operations and burst loadings. The resulting findings were instrumental in alerting Shuttle Management to the possibility that lifing methods based upon pressure as the load variable could provide non-conservative life predictions.

Indeed after independent verification it was found that liner contributions were not included in the main stress rupture database for Kevlar COPV test articles. Applying graphical analysis methods to experimental strain-pressure measurements of the test articles provided the evidence needed to recalibrate the database for more accurate life predictions of the flight hardware. Further investigation of the shuttle flight hardware vendors stress report with these methods, determined that a non-conservative lifing approach had been employed in their stress rupture analysis. The first ever analysis of actual qualification burst data revealed that the nominal fiber stress at burst was in some cases 23% lower than what the vendor used to predict stress rupture life. After withstanding independent verification by finite element analysis, these specific results were found to have the greatest impact on the residual life and perceived safety and quality of the Shuttle Fleets COPV hardware. The analytical tools developed in this work have since been transferred to Shuttle Operations to assist them in modifying Shuttle COPV operations to extend life. The model has also been applied to estimate any beneficial effect that creep deformation may have on extending life. The analyses, finding and recommendations are contained in the forthcoming coauthored document: **“Technical Consultation of the Shuttle Kevlar Composite**

Overwrapped Pressure Vessel Safety for Flight Concern” 04-016-E Report, (current Draft: Version 12 11-10-04).

Durability of Polymer Composite Flywheel Energy Storage Systems for Space Flight

Successful space flight operations require onboard power management systems that reliably achieve mission objectives for a minimal launch weight. Due to their high specific energies and potential for reduced maintenance and logistics, composite flywheels are an attractive alternative to electrochemical batteries. In support of this effort an experimental test program providing unique design data essential to the safety and durability of flywheel energy storage systems for the international space station and other manned space flight applications. Analysis of the experimental data [1, 15, 16] demonstrated that the compressive stress relaxation of composite flywheel rotor material is significantly greater than the commonly available tensile stress relaxation data. Durability analysis of compression pre-loaded flywheel rotors requires this data to make correct safe life predictions for use in the international space station. Considerable effort beyond normal work requirements was invested to insure that these experiments and their design implications were analyzed and published. This accomplishment was recognized by NASA with a **2002 Space Flight Awareness Team Award**: For outstanding support given to the Rotor Safe Life Program in developing a basic understanding of time-dependent behavior of pre-loaded composite flywheel rotors for the international space station.

Aviation Safety

A thorough review of the Hopkinson Bar test literature was made and a working Program document was created containing the fundamental governing equations and a methods description. Local facility visits were made providing insight to the Hopkinson Bar methods employed by Prof. Amos Gilat at Ohio State University and Prof. Vikas Prakash of Case Western Reserve. Two opposing approaches to Tensile Hopkinson Bar testing are reviewed: Prof. Gilat’s tensile storage bar approach and Prof. Prakash’s striker bar generated tensile wave. A preliminary design EXCEL worksheet was developed for the storage bar approach along with parts list and photos.

Guided by fundamental equations, experimental work focused on bar calibration methods for GRC’s existing compression SHB set-up. New Wheatstone completion bridge boxes were introduced for the foils resistance strain gages on the input and output bars. Laser/photo detector pairs were added to the experimental set-up to enable transit time measurements of the striker bar over a fixed distance immediately prior to impact. Measurements of the striker bar velocity V_s and the maximum amplitude of the strain pulse in the input bar ϵ_i for a number of different striker bar velocities were made. Ideally the two quantities obey the following relation for elastic striker-input bar collisions.

$$\epsilon_i = \frac{V_s}{2 \cdot c_b}$$

The slope of a linear least square fit of the data was used to determine the input bar elastic wave speed c_b . The calibration activity produced a 14% slower bar wave speed than expected based on the square root ratio of elastic modulus E_b to density ρ_b

$$c_b = \sqrt{E_b / \rho_b} .$$

Distance traveled and transit time between input and reflected waves yielded larger wave speeds; mean values were found to be only about 4% slower than analytically predicted. The bar wave speed is a scaling parameter to compute strain rate and the time integrated strain response of a SHB specimen from measure strain pulses. It is important to know how accurately this parameter can be measured and how well it agrees with fundamental theory. However SHB practitioners are not in agreement regarding the need for this type of bar calibration wave speed measurements.

Some initial testing of annealed IN718 was made which produced insignificant reflected wave and small permanent deformation. High hardening rates were suggested as the controlling factor and that greater area mismatch between specimen and bar would be required to achieve the desired high strain rates and large deformations in this material. Here is where the SHB literature guiding experimental design seemed significantly lacking. Analytical formulae had been derived to estimate time to equilibrium for a given specimen geometry but no guidance on the expected strain rate and actual stress strain response could be found.

Applying theoretical principles of guided waves in bars, recurrence equations were derived for elastic wave reflections in an SHB specimen due to a Heavy-side step wave and waves with a linear ramp. The recurrence relations are series functions involving reflection and transmission coefficients governing the behavior of elastic waves at dissimilar interfaces. The reflection and transmission coefficients are based on the impedance ratios between the bars and specimen. Using applied mathematics, solutions for stress and strain rate up to the j th internal reflection were derived. Limits as the number of internal reflections approached infinity were also determined. Extremely valuable insight and useful relationships were derived from this effort. These are listed below:

Elastic Response to Step Waves

1. Stress equilibrium in the specimen is controlled by the internal reflection coefficient; the additional increment of stress with each reflection becomes smaller. The lower the ratio of specimen to bar impedance the greater the number of reflections required for specimen equilibrium to occur and convergence to constant stress.
2. The solution for strain rate sets a more accurate upper bound for the maximum possible strain rate in any SHB experiment. In the analytical solution it is the difference between the first reflected wave at the bar specimen interface and the input wave. Thereafter strain rate decreases in magnitude and is never constant. It becomes zero when specimen stress becomes constant.

1. Stress equilibrium in the specimen is controlled by the number of reflections for bar to specimen impedance ratios less than 3.0. In these cases the increment of stress increase with each reflection quickly becomes constant and the ratio of stress increment to total stress has the form of the function $(1/j)$ where j is the total number of reflections. A 5% increase in total stress occurs after 20 reflections. For bar to specimen impedance ratios greater than 3.0 the convergence to a constant stress increment will take longer than 20 reflections and is dependent upon the internal reflection coefficient. If the ramp reaches a plateau of constant amplitude the increment of stress with each reflection will diminish in magnitude. While this will accelerate the equilibration of stress in the specimen it can be shown to reduce specimen strain rate to zero.
2. Specimen strain rate response is a non-linear monotonically increasing function that asymptotically approaches a constant magnitude. The duration required to reach a constant magnitude is dependent on the internal reflection coefficient. Higher ratios of bar to specimen impedance require a greater number of reflections before the plateau is acquired. The magnitude of the constant strain rate plateau $\dot{\epsilon}_{\max}$ is governed by the following simple relation:

$$\dot{\epsilon}_{\max} = \frac{\epsilon_{\max}}{\tau_o} \frac{A_b}{A_s} \frac{E_b}{E_s}$$

where A is the cross-sectional area and E is the elastic modulus; the b and s subscripts are for bar and specimen respectively. ϵ_{\max} is the magnitude of the input strain wave plateau and τ_o is the time over which the linear ramp to maximum strain occurs. This upper bound is only attained if τ_o is of sufficient duration for the series to converge. This effectively constrains τ_o to a minimum value for which the relation is meaningful; smaller values would artificially elevate the upper bound while physically the strain rate response is truncated. This is because the strain rate response symmetrically reverses once the plateau is reached and asymptotically returns to zero. Strain rate is only constant for sufficiently long ramp times in elastic ramp wave problems.

The above results are closed form and exact for elastic materials and would be directly applicable to the analysis of the high strain rate response of elastic brittle materials. The underlying equations have been programmed in EXCEL and MATHCAD worksheets. Some insight into the behavior of elastic-plastic materials with different hardening rates can be gleaned from these formulae however it would be desirable to obtain more accurate models of the stress and strain rate response for such materials. An exhaustive review of the theory of plastic wave theory provided the foundation to construct such a model for bilinear elastic-plastic behavior. The model required the derivation of reflection and transmission coefficients for an interface between and elastic and elastic-plastic material. This was successfully done for a variety of relevant cases by conserving particle velocity and stress equilibrium across bi-material interfaces. These relations were then used to simulate the elastic-plastic response of a specimen

subjected to Heavy-side step loading. A MATHCAD program was written that simulates the elastic ring-up to the yield point and the response of the specimen post yield. The main conclusions follow:

Elastic-Plastic Specimen Response to a Step Wave

1. The initial elastic specimen response is identical to the formerly derived results during the elastic ring-up. At the yield bifurcation point the stress increment abruptly decreases and all future stress increments are smaller depending upon the hardening rate of the bilinear material. For materials approaching elastic-perfectly plastic response in the limit, all subsequent stress increments become vanishingly small. Compared to the ambient stress in the specimen which is the flow stress these subsequent stress increments are insignificant so the specimen can be considered to be in stress equilibrium. Thus an elastic-plastic material with low hardening could be considered in equilibrium once yield is surpassed. Materials with hardening rates approaching the elastic modulus of the material will not converge to stress equilibrium much sooner than had the material not yielded at all.
2. The maximum strain rate response of the specimen is the difference between the input and reflected elastic wave. During the elastic portion of the ring-up strain rate decreases monotonically until the yield point is reached. At the bifurcation point the strain rate decreases more slowly. For behavior approaching an elastic-perfectly plastic material, the strain rate becomes nearly constant. Materials with hardening rates approaching the elastic modulus of the material will respond with a continuously decreasing strain rate. The notion of constant strain rate response to step wave loading is completely dependent upon hardening rate of the material.
3. If hardening rate correlates positively with strain rate, an initially high strain rate and high hardening rate will reduce strain rate in subsequent wave reflections. Thus resulting in lower subsequent hardening rates. One would expect that the response would converge towards the minimum hardening rate and this hardening rate would control the remaining strain rate response of the specimen. The only way to achieve a constant strain rate in an SHB experiment for materials with steep tangent moduli is to induce it through the application of linear ramp wave. This is accomplished through the technique of pulse shaping.

The results of the elastic-plastic model are intuitively correct and agree with published input and reflected wave data for SHB experiments. The models are the first known to go beyond stress equilibrium guidelines and provide quantitative predictions of expected strain rates for elastic-plastic materials. Here quasi-static material data can be used to provide valuable baseline specimen performance predictions. Indeed the expected specimen response can be bracketed by the results of purely elastic and elastic-plastic analyses. Detailed presentation of these analyses is being drafted in a Hopkinson Bar Analytical Methods report.

PMMA Weld Evaluation for Test Chamber—International Space Station

Participated with NASA colleagues in a materials and design evaluation team certifying chemical welded joints of PMMA pressurized vessels for specialized experiments on Space Station. Collaborated in the development of a test program to examine the strength of chemical welded joints in the presence of notches. Special biaxial experiments were made using the Brazilian Nut specimen to examine fracture toughness in mode I and Mode II fracture modes. The data were analyzed with respect to an upper bound stress analysis of the pressure vessel to provide operation margins to the design team. Results are contained in the internal Final Report for CFE-TPRO-017, "PMMA Material Test Result for the Capillary Flow Experiments (CFE)" by Brad Lerch and John Thesken. [5]

Hygrothermal Fatigue Degradation of AS4/PR500

Opportunities to design more efficient aero-engine using polymer matrix composites is of interest to a variety of commercial engine companies and the NASA Glenn Research Center. Assessing the durability and fatigue capability of these materials for such complex environmental and mechanical loadings is essential to accelerate the insertion of these materials in aero-engine applications. Presently hygrothermal fatigue and mechanical fatigue testing is conducted in series. Durability testing of fan exit casing material AS4/PR500 is underway and examines the fully reversed fatigue response at elevated temperature following 30,000 hrs of Simulated Engine Mission Exposure testing. Led a problem resolution team in the continuation of an independent assessment of long-term hygrothermal and mechanical fatigue degradation for polymer composite fan structures. The outstanding program begun by Castelli and co-workers [15, 18] required 3 years of hygrothermal cycling yielding a valuable pedigree of degraded material for structural testing. Mentored a visiting Hungarian graduate student, Mr. Krisztian Toth, who joined the experimental program to characterize the durability of polymer matrix composite (PMC) subjected to 30,000 hr of hygrothermal fatigue followed by mechanical fatigue. Published completed tests and analyses already have given design data and guidelines of significant importance to the nation's aircraft engine manufacturers. These new experimental results demonstrate that significant degradation is attributed to hygrothermal cycling and must be considered in designing composite structures requiring long term durability. New ways to address these issues were developed with colleagues at a DARPA AIM-C Durability workshop.

Titanium Matrix Composites

New manufacturing technologies are now capable of producing uniformly distributed particle strengthened titanium matrix composites (TMC's) at lower cost than many types of continuous fiber composites. While good specific properties have been reported, little is known about the deformation and damage behavior of TMC's. Since particulate reinforced metals are known to have durability issues in certain states of stress and loading modes, an exploratory test program was initiated and completed. [17] Tensile and low cycle fatigue testing was made at 427 °C, a benchmark test temperature common to several previous titanium test programs. At 10 weight percent particle concentrations, the material stiffness of the TMC was improved 19% over the un-reinforced titanium alloy when tested at 427 °C. While fatigue life is reduced relative to the un-reinforced material, it is noteworthy that low cycle fatigue at 1% strain range, does not

degrade the composites superior material stiffness. At these temperature levels, particulate reinforced TMC may be an attractive alternative to other lightweight materials for stiffness driven applications. By careful exploration of the materials limitations and benefits it should be possible to assist the propulsion system designer in selecting appropriate applications for these materials. In this regard, an experimental program has been designed to characterize this material. The positive results have also motivated a companion proposal to the Air Force in the **JSTAB Submission** entitled **“Technology Base for the Accelerated Insertion of Particulate Reinforced Metallic Composites into the JFS Platform.”**

Performance Evaluation of Organics in Stirling Engine Applications

The advanced Stirling radioisotope generator contains a variety of components that constructed of metallic laminae and plates that are assembled using organic adhesives. The a desired service life for such devices being in excess of 15 years the need to select and verify the performance of longer life-more durable organics for alternator components. The Polymers Group has conducted a program to:

- Characterize Adhesive Cure Kinetics and Aging Mechanisms
- Develop Adhesion Performance Evaluation Test Methodology/protocol and Generate Performance Simulation Data
- Identify Service-induced Adhesion Performance Degradation Mechanism
- Develop Component Lifetime Prediction Model

Analytical and experimental design support has been provided to this effort to insure that the complex stress and deformation state is correctly simulated in the proposed experimental program. This included a review of the combined stress state based on finite element results used to indication of the combined loading modes. The influence of fatigue/creep interaction, mean load effects, dimensional stability has also be considered in the evaluation and methods for biaxial creep testing were proposed. In collaboration with Cincinnati Testing Labs, rigging and methods for component level tests have been developed. Advised on the acquisition of high cycle fatigue equipment and methods for testing lap shear coupons at high frequency. Conducted preliminary analysis for the insertion of weight saving polymer matrix composites in Stirling components and advised on the feasibility of weight saving opportunities.

Courses and Workshops

- 2004 COPV ITA Technical Interchange Meetings: JSC, LaRC, and GRC
- Innovative Problem Solving Using TRIZ 32 hrs, 2004, NASA-GRC/OAI
- MATHCAD Seminar, 1.5 hrs, NASA
- Structure of Biological Materials, 24 hrs, OAI

- Power Reading, 8hrs, 2003, NASA-GRC
- Space Craft Structural Design Spacecraft Structural Design, August 9, 2002, NASA-GRC
- Structural Sandwiches: Theory/Analysis/Design, April 1-2, 2002, NASA-GRC
- Mechanics of Textile Composite Materials, February 5 & 6, 2002, NASA-GRC
- TestExpress Course Version 4.0, November 13, 2002, NASA GRC
- Power Presentations December 19–20, 2002, NASA GRC
- Invited Attendee DARPA AIM-C Durability Workshop, December 5–6, 2001, Los Angeles, California
- Manufacturing Problem Prevention Program Sandwich Structures for Space Systems, February 26–27, 2002, California
- Meeting of ASTM Committee D-30: Composite Materials, March 11–4, 2002, Pittsburgh, Pennsylvania. Contributed to the drafting and editing of Standard D4762

Awards

- 2004 NASA Group Achievement Award for determining the benefits and trade-offs for out of plane stitched polymer matrix composites for the NASA Reusable Launch Vehicle.
- 2004 Ohio Aerospace Service Award in recognition of personal commitment, dedication and performance
- 2003 NASA-GRC Propulsion and Power Program Award in recognition of contributions and outstanding support
- 2003 Ohio Aerospace Service Award in recognition of personal commitment, dedication and performance
- 2002 NASA Space Flight Awareness Team Award: For outstanding support given to the Rotor Safe Life Program in developing a basic understanding of time-dependent behavior of pre-loaded composite flywheel rotors for the international space station.

Publications

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10. J.C. Thesken, M. Melis, E. Shin, J. Sutter, C. Burke, and J. Fink, 2003, "Design Analysis and Thermomechanical Fatigue of a Polyimide Composite for Combustion Chamber Support," High Temple Workshop 23, Jacksonville, Florida, February 10-13, 2003.
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